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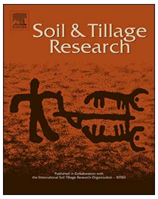

Improved thermo-time domain reflectometry method for continuous in-situ determination of soil bulk density

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ABSTRACT

Quantifying the dynamics of surface soil bulk density (ρ_b) is important for characterizing water, heat, and gas exchanges in agricultural and environmental applications. Unfortunately, very few approaches are available for continuous in-situ monitoring of ρ_b. The soil heat capacity-based (*C*-based) thermo-time domain reflectometry (thermo-TDR) approach has been used to measure ρ_b in-situ, but this approach gives ρ_b estimates with relatively large errors. In this study, we present a new soil thermal conductivity-based (λ-based) thermo-TDR approach for continuous and automatic determination of ρ_b variation in-situ. An error analysis, literature data, and field experiments were used to evaluate the performance of the *C*-based and λ-based approaches. The error analysis undertaken on hypothetical soils indicated that the new λ-based approach was less sensitive to errors in the measurement inputs than was the *C*-based approach when the same relative errors occurred, except on very dry soils. Thermo-TDR measurements reported in the literature on seven soils showed that the new λ-based approach provided more accurate and precise ρ_b estimates, with coefficient of determination (R^2) of 0.70 and root mean square error (RMSE) of 0.103 Mg m^{-3}, than did the *C*-based approach which gave ρ_b with R^2 of 0.32 and RMSE of 0.178 Mg m^{-3}. Two field experiments were conducted to test the performance of the new λ-based thermo-TDR approach for monitoring ρ_b dynamics. The results showed that following tillage surface ρ_b increased by about 35% within 40 days. The ρ_b obtained by the λ-based thermo-TDR approach agreed well with independent core sampling measurements, with an average RMSE of 0.122 Mg m^{-3}. The *C*-based approach failed to give acceptable ρ_b estimates in most cases because of probe deflection and environmental factors. We conclude that the new λ-based thermo-TDR approach is a promising method for continuous in situ measurements of ρ_b.

1. Introduction

Cultivated fields can undergo significant changes in soil bulk density (ρ_b) due to agricultural management and climate effects (Strudley et al., 2008). In general, the surface soil has the lowest ρ_b of the year immediately after tillage. After that, ρ_b increases as particles resettle under the influences of rain, irrigation, and traffic (Meek et al., 1992; Osunbitan et al., 2005). Previous studies have demonstrated that surface ρ_b can change more than 40% through annual cycles of disturbance associated with agricultural practices (Osunbitan et al., 2005; Logsdon, 2012; Liu et al., 2014). Freeze-thaw cycles, shrink-swell processes, erosion, and deposition also alter surface ρ_b and structural arrangement (Oztas and Fayetorbay, 2003; Hamza and Anderson, 2005; Logsdon, 2012).

Transient ρ_b affects surface soil gas transport and thermal-hydraulic processes. If ρ_b and related properties (e.g., soil total porosity) are taken as being constant over time, large errors can occur, for example, in the estimation of carbon dioxide production in tilled field soil with time-variable ρ_b (Han et al., 2014). Soil thermal properties are directly related to the solid constituents in soil, and they are generally estimated using models including ρ_b as an independent variable (de Vries, 1963; Lu et al., 2014; Tian et al., 2016). The variation in ρ_b caused by tillage, compaction, and runoff over the surface has significant impacts on soil air permeability, cone penetration resistance, hydraulic conductivity, water retention characteristics, and infiltration capacity (Osunbitan et al., 2005; Assouline, 2006a, b ; Strudley et al., 2008; Weisskopf et al., 2010; Alaoui et al., 2011; Gao et al., 2016). There is a need for in-situ monitoring of ρ_b dynamics for improved understanding of the water, gas, and heat transport in surface soil.

The core method is commonly used for determining ρ_b. When it is done carefully to avoid sample compaction, the core method is considered accurate, but also time consuming and destructive. The soil

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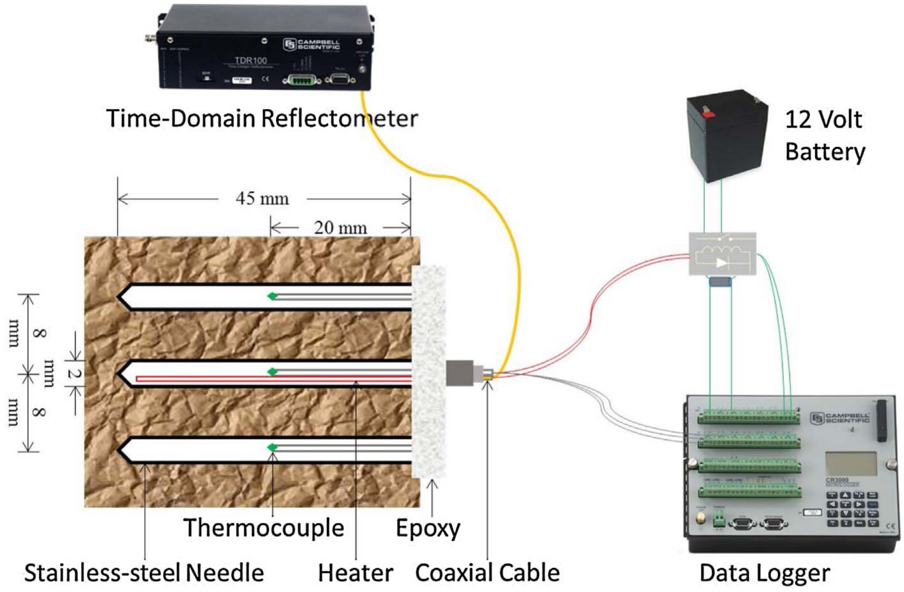

Fig. 1. A schematic view of the thermo-time domain reflectometry measurement instruments (not to scale).

sampling probes used to obtain soil cores for subsurface ρ_b measurements can lead to the compaction or stretching of the soil cores during sampling (Walter et al., 2016). Under dry soil conditions, the core method is difficult to perform and subject to large measurement errors (Mouazen and Al-Asadi, 2018). Excavation methods (e.g., rubber balloon method and sand replacement method) have also been used for ρ_b measurements, but generally only apply to relatively large soil samples (Blake and Hartge, 1986). There are some indirect methods available that utilize laser profilers, thermo-time domain reflectometry (thermo-TDR), and combined sensor devices (e.g., combining near infrared spectroscopy (NIR) and frequency domain reflectometry (FDR) or combining NIR, draught and depth sensors) to estimate ρ_b or total porosity (Ochsner et al., 2001; Liu et al., 2008; Sun et al., 2009; Quraishi and Mouazen, 2013; Al-Asadi and Mouazen, 2014). For agricultural soils, ρ_b is usually small following tillage and tends to increase with time under the influences of gravity, compaction, and subsequent rainfall or irrigation. Among all the mentioned methods, the thermo-TDR technique is the only one that can be used to monitor in-situ ρ_b automatically and continuously (Liu et al., 2014; Lu et al., 2017).

Ren et al. (1999) developed the thermo-TDR probe for simultaneous measurement of soil thermal properties (i.e., volumetric heat capacity, C, thermal diffusivity, α, and thermal conductivity, λ) and volumetric water content (θ_w). Ochsner et al. (2001) and Ren et al. (2003) applied the sensor to determine ρ_b by using the relationship between ρ_b and thermo-TDR measured C and θ_w. However, the C-based thermo-TDR approach may give ρ_b estimates with relatively large errors due to the influences of sensor needle deflection and environmental factors such as, ambient temperature drift and water flow in the soil (Ren et al., 2003). Liu et al. (2008) introduced a robust sensor design that had improved the accuracy of the C-based approach. The robust thermo-TDR probe also produced reliable ρ_b estimates in-situ (Liu et al., 2014). Some investigators also tested the possibility of deriving ρ_b from thermo-TDR measured λ and θ_w by using inverse λ-prediction models that associate λ with ρ_b and θ_w (Olmanson and Ochsner, 2008; Lu et al., 2016). The λ-based thermo-TDR approach may have an advantage over the C-based approach for estimating ρ_b in-situ because needle deflection significantly affects the accuracy of C measurements, but has less influence on λ measurements (Kluitenberg et al., 1995, 2010; Lu et al., 2016).

Lu et al. (2016, 2017) used an empirical λ model to derive ρ_b from thermo-TDR measured λ and θ_w. However, the previous empirical λ-prediction models may not well represent all soil conditions. In particular, our analysis indicated that the Lu et al. (2016) method performed poorly on some coarse textured soils (see Section 3). Recently, Tian et al. (2016) developed a simplified de Vries model for estimating λ with soil texture information, ρ_b, and θ_w. This model provides accurate and consistent λ estimates, and it has the potential for use in inversely estimating ρ_b from thermo-TDR measured λ and θ_w. Additionally, the simplified de Vries model is a physically based model, and soil-specific calibration of the model parameters can be done within the model framework.

This paper aims to introduce a new λ-based thermo-TDR approach using the simplified de Vries model for monitoring ρ_b variations continuously over time. The performances of the C-based and λ-based approaches for determining ρ_b are evaluated and compared by using error analysis, literature data, and field experiments.

2. Materials and methods

2.1. Thermo-TDR method

Ren et al. (1999) combined a heat pulse sensor and a time domain reflectometry probe into one unit (i.e., thermo-TDR probe) and applied it for simultaneous measurement of soil thermal properties (C, α, and λ), θ_w, and electrical conductivity. Liu et al. (2008) improved the design of the thermo-TDR probe making the sensor more robust by increasing needle sizes (needle diameter, length, and spacing) compared to Ren et al. (1999). The thermo-TDR probe consisted of three parallel stainless steel needles (4.5-cm length, 2-mm diameter, and 8-mm needle-to-needle spacing) fixed in an epoxy body (Fig. 1). A heating wire was enclosed in the middle needle and thermocouples were installed at the middle locations of all three needles. For soil thermal property measurements, a heat pulse was released via the heating wire, and the soil temperature responses (T, °C) at a distance r from the heater were measured by the thermocouples in the outer needles. In the present study, the heating power was supplied by a 12-volt battery and recorded by a data logger (CR3000, Campbell Scientific, Logan, UT) along with the soil temperature data (Fig. 1). Soil thermal properties were extracted from the temperature-time curves using short-duration heat-pulse theory (Bristow et al., 1994),

$$\Delta T(r,t)=\begin{cases}\dfrac{-q'}{4\pi C\alpha}\mathrm{Ei}\left(\dfrac{-r^2}{4\alpha t}\right) & 0<t<t_0\\ \dfrac{q'}{4\pi C\alpha}\left\{\mathrm{Ei}\left[\dfrac{-r^2}{4\alpha(t-t_0)}\right]-\mathrm{Ei}\left(\dfrac{-r^2}{4\alpha t}\right)\right\} & t>t_0\end{cases} \tag{1}$$

where ΔT is the temperature change (°C), which is calculated as the